A rotor wake – rotor tonal interaction noise computation procedure for contra-rotating fans

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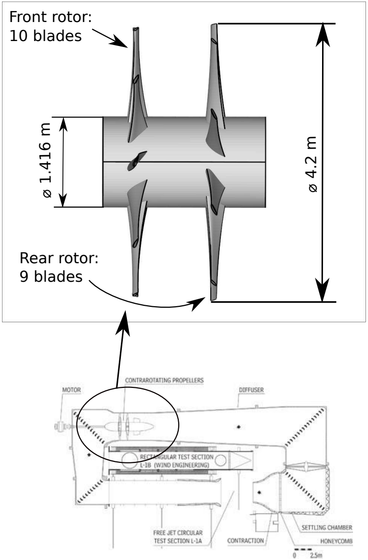
Table of Contents

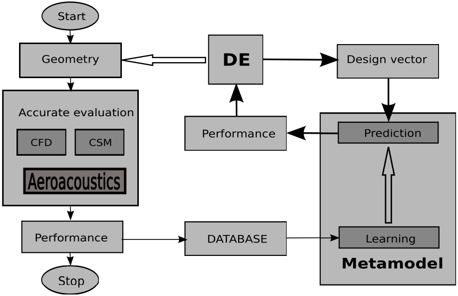
Introduction

- CROR architectures are substantially more efficient than normal propellers, but a major drawback is the high noise emission.
- Development of an aeroacoustic evaluation procedure that can be implemented in the phase of preliminary design of a CROR.
- Application case: contra-rotating fans of VKI-L1 wind tunnel.



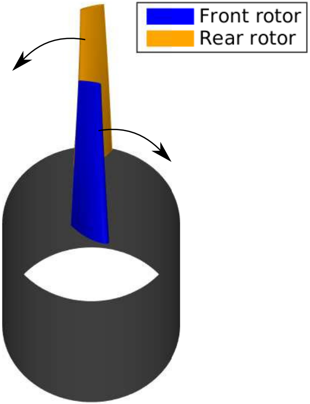
Introduction

- An aerodynamic - aeroacoustic optimization of this geometry has been performed.
- In-house optimization software: CADO.
- Simplified noise evaluation method.
- The results of this optimization will now be analysed in the light of a more advanced noise computation algorithm.

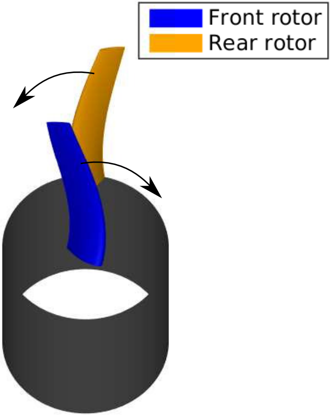


Geometric configurations of interest - effect of lean and sweep

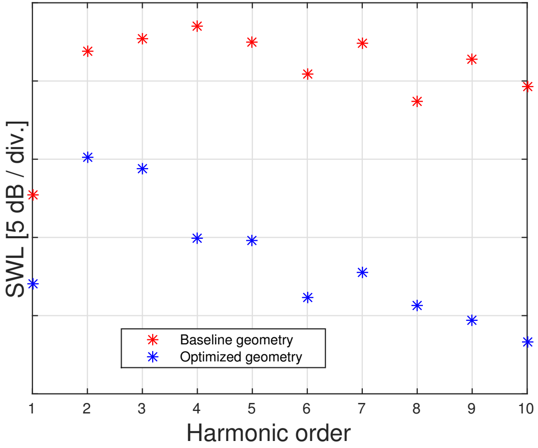
Baseline geometry

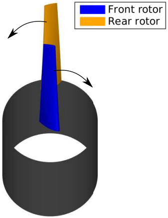


Optimized geometry



Far-field tonal noise spectrum





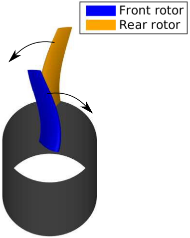
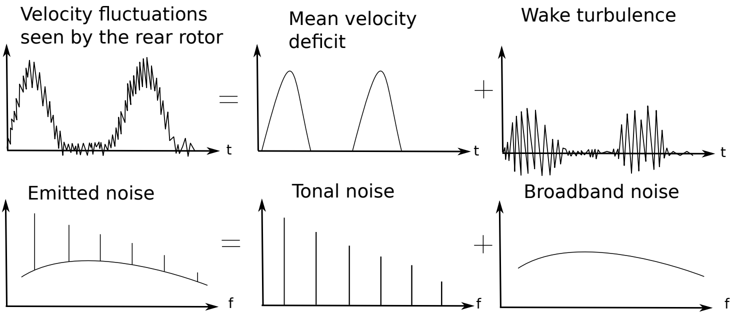


Table of Contents

Table of Contents

Linearised aeroacoustic theory

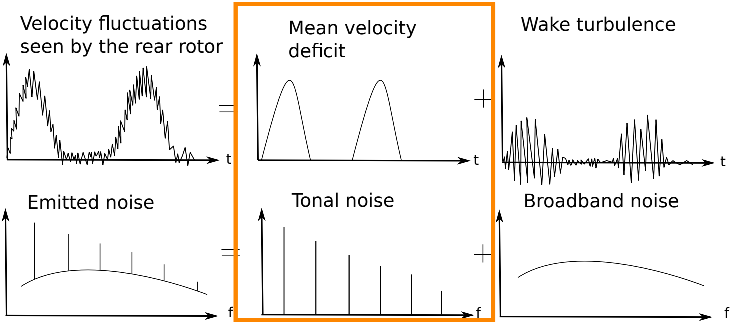


Decoupling of the aeroacoustic phenomena related to wake interaction:

- mean velocity variation in the wake causes tonal noise;
- wake turbulence causes broadband noise.

(Fournier, 1988)

Linearised aeroacoustic theory



Decoupling of the aeroacoustic phenomena related to wake interaction:

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(Fournier, 1988)

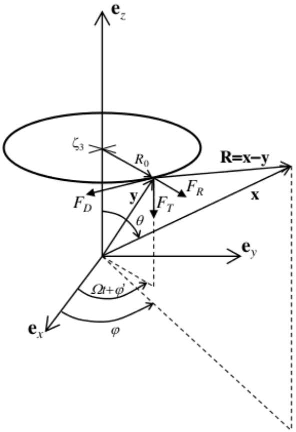
Sound pressure emitted at a given harmonic of the BPF of the rear rotor (Goldstein, 1976):

$$p'_{nB} \sim -\frac{iBk_{nB}}{4\pi}\frac{e^{-ik_{nB}x}}{x}\sum_{p=-\infty}^{+\infty} e^{-i(nB-p)(\phi-\phi_0-\pi/2)}\dots$$

$$\Big(J_{-nB+p}(-k_{nB}R_0\sin\theta)F_p^{(T)}\cos\theta\dots$$

$$-\frac{nB-p}{k_{nB}R_0}J_{-nB+p}(-k_{nB}R_0\sin\theta)F_p^{(D)}\dots$$

$$-\,iJ'_{-nB+p}(-k_{nB}R_0\sin\theta)\sin\theta\ \ F_p^{(R)}\Big).$$

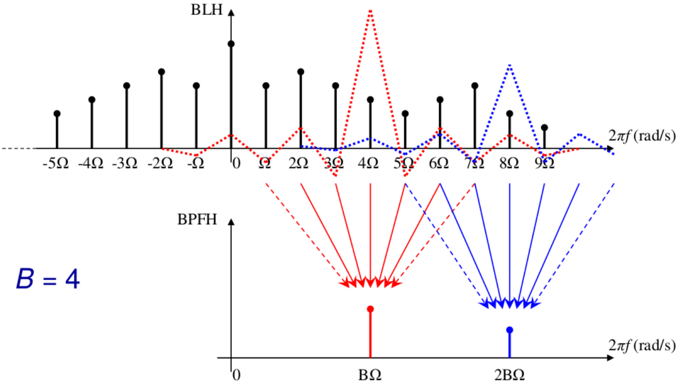


x, ϕ, θ: spherical coordinates of the listener position.

ϕ_0: relative azimuthal displacement of the source locations $\rightarrow$ retarded time effect.

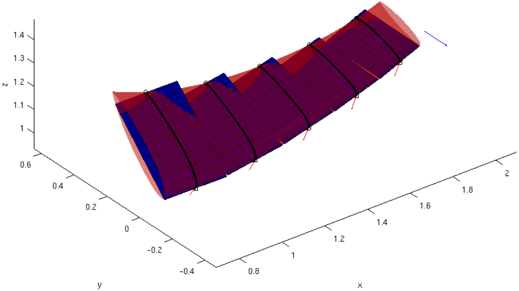
Ffowcs Williams and Hawkings analogy

Bessel functions modulate the Doppler frequency shift during blade revolution.



Approximation of the blade geometry with rectangular strips

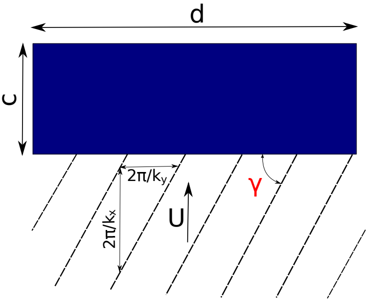
- Amiet's theory approximates slightly cambered airfoils with flat plates.
- Dividing the blade in rectangular strips allows to take into account spanwise variation of flow conditions.
- The overall noise is the sum of the noise emitted by each strip.



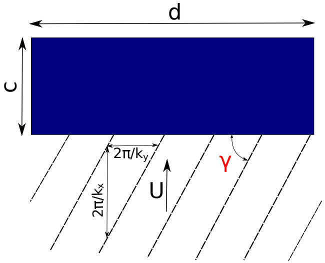
Formulation of the unsteady lift

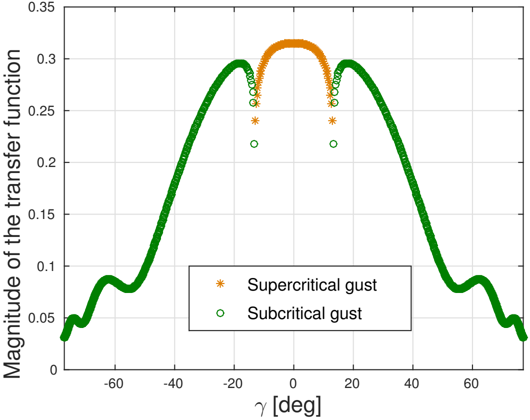
$$L(k_x, k_y) = 2\,\pi\,\rho_0\,U\,(c/2)\,\hat{\hat{w}}(k_x, k_y)\,G(c_0, (c/2), k_x, k_y, U)\ldots$$
$$i\,(\exp(-i\,k_y\,d/2) - \exp(i\,k_y\,d/2))/k_y$$

$\hat{\hat{\mathbf{w}}}(\mathbf{k_x}, \mathbf{k_y})$ is the double spatial Fourier transform of the velocity disturbance.
G is the aerodynamic transfer function from the velocity disturbance to the unsteady lift. (Amiet, 1975)



Effect of γ on the transfer function computation





The magnitude of the response function can be reduced to less than a third by increasing the skewness of the wake.

Table of Contents

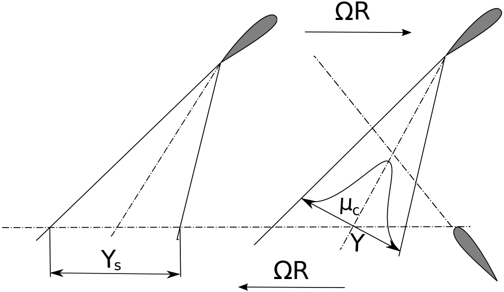
Synthetic wake generation
General equations

Mathematical model based on the empirical correlations of Raj and Lakshminarayana (1976).
Decaying of the defect in mean velocity at the wake centerline:

$$\frac{\mu_c}{\overline{U}} = \exp\left[-\frac{\pi^2}{14}\left(\frac{s}{S'}+3.46\right)\right]$$

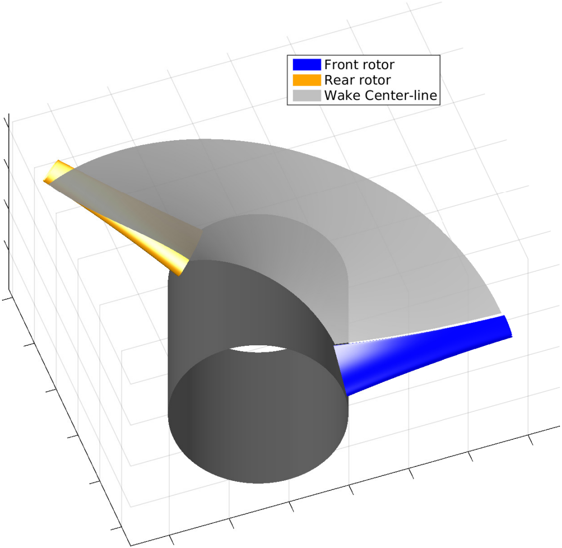
being s the streamwise direction and S' the blade spacing (projected).
Wake width variation:

$$\frac{Y_S}{Y_{S0}} = 1.61\left(\frac{s}{S'}\right)^{0.23}$$



Synthetic wake generation

Application to baseline configuration



Synthetic wake generation

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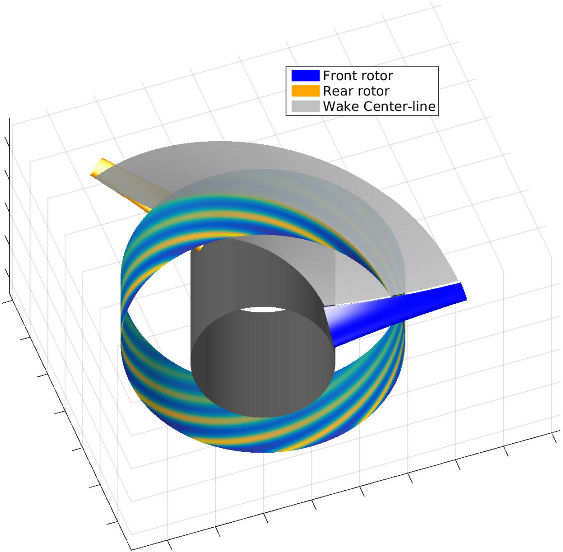
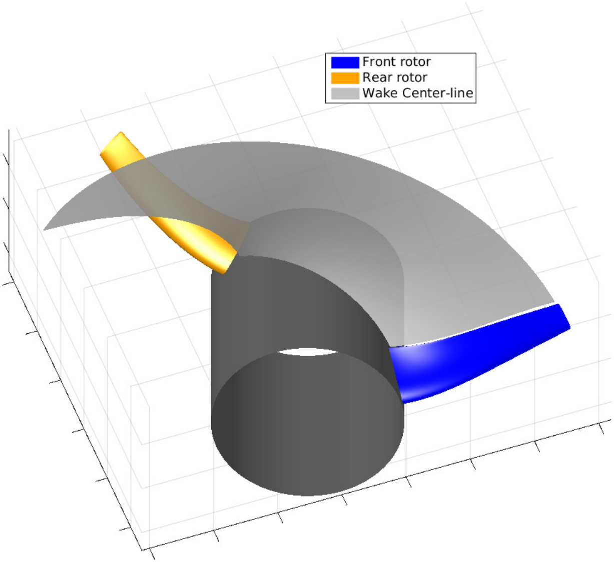


Synthetic wake generation

Application to optimized configuration



Synthetic wake generation

Application to optimized configuration

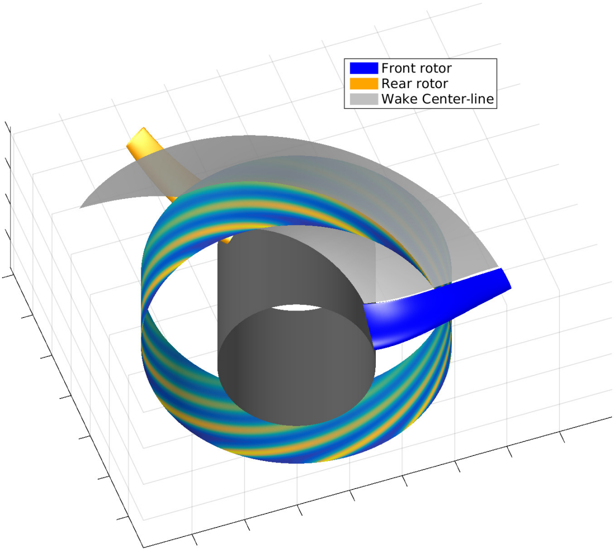
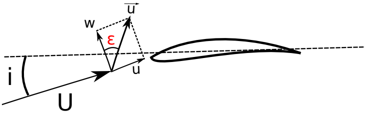
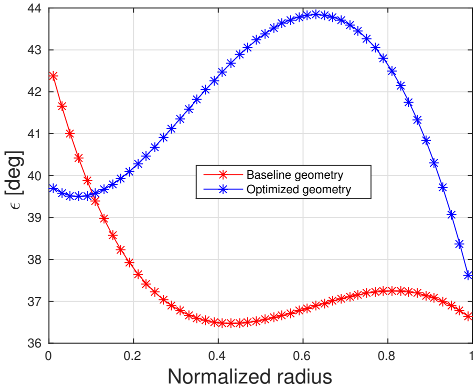


Table of Contents

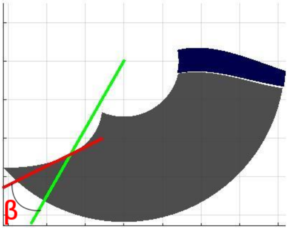
Projection of the upwash component of the velocity disturbance

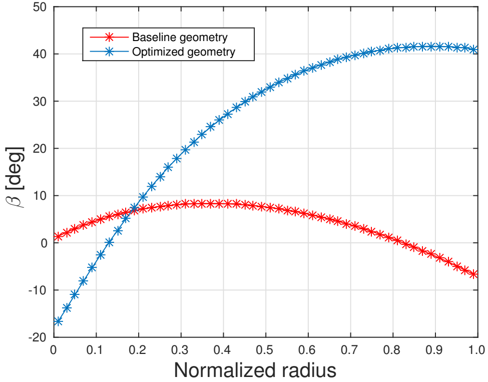


The upwash component of the velocity disturbance is responsible for the major part of the unsteady lift.



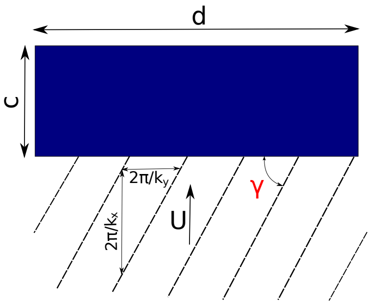
Inclination of the wake center-line in the secondary plane

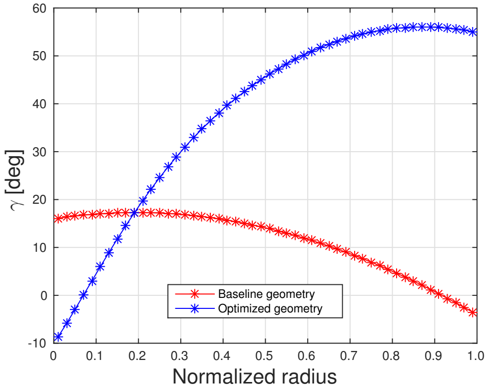




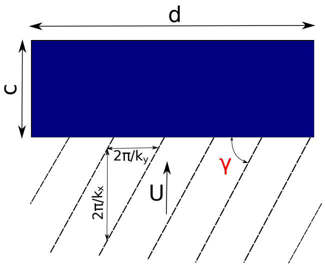
β is invariant with the rotation of the wake. Its computation is necessary to project the wake in the frame of reference attached to each rear blade strip.

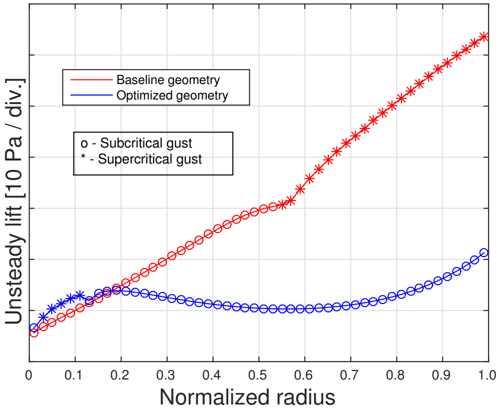
Inclination of the incoming gust, γ





The incoming wake is projected, at every radial position, in the plane of the rear rotor strip.





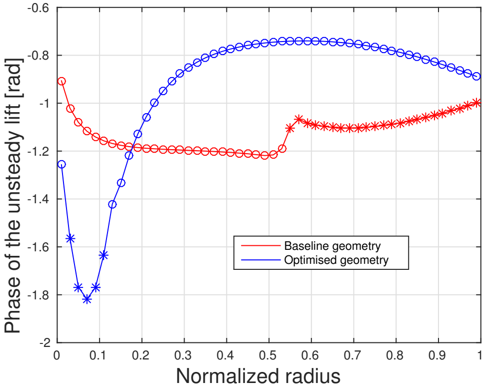
First BLH magnitude.

Conclusions and future work

- The synthetic wake generation algorithm has been useful to understand the geometric parameters that influence the wake-blade interaction.
- The skewness of the wake seen by the rear rotor is the key parameter that can reduce the blade loading harmonics and thus the emitted noise.
- Secondary flow phenomena have not been taken into account. The noise computation will be based on CFD data. RANS simulations will be used to reduce computational cost (implementation of a wake extrapolation procedure).
- Modelling of broadband noise related to incoming turbulence.

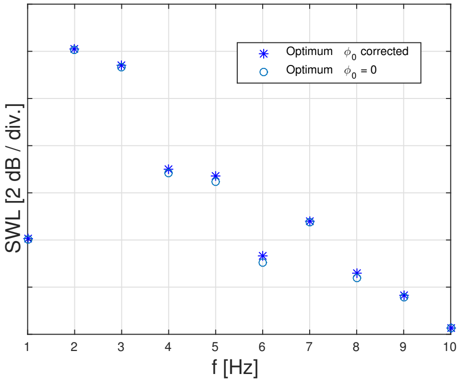
Thank you for your kind attention.
Any question?

Retarded time effects in the wake-rotor interaction



Retarded time effects in the propagation of noise

Optimized configuration



Publications

- G. Grasso, J. Christophe, C. Schram, T. Verstraete, *Aerodynamic, aeroacoustic and structural optimization of a contra-rotating Fan*, 15th International Symposium on Transport Phenomena and Dynamics of Rotating Machinery, ISROMAC-15, Honolulu, USA, 2014.
- G. Grasso, J. Christophe, C. Schram, T. Verstraete, *Influence of the noise prediction model on the aeroacoustic optimization of a contra-rotating fan*, 20th AIAA CEAS Aeroacoustics Conference, Atlanta, USA, 2014.
- G. Grasso, J. Christophe, C. Schram, *Numerical performance and accuracy of wake interaction noise prediction models*, International Conference on Noise and Vibration Engineering, Leuven, BE, 2014.
- G. Grasso, J. Christophe, C. Schram, *Broadband trailing-edge noise prediction of a four-bladed axial fan* , International Conference on Fan Noise, Technology and Numerical Methods, Lyon, FR, 2015.